Photonic Frequency Synthesis and Control with Whispering Gallery Mode Microresonators

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Dielectric microresonators with whispering-gallery modes (WGMs) may possess high Q-factors ($10^8 - 10^{10}$), small size, and small mode volumes. Nonlinear and/or tunable WGM resonators are useful in many fundamental and practical applications. We report here on experimental and theoretical studies of electro-optical tunability of WGMs in high-Q monolithic lithium niobate resonators and applicability of such resonators for light modulation and filtering. Properties of an optoelectronic microwave oscillator (OEO) based on an WGM $LiNbO_3$ resonator are discussed.

Wavelength demultiplexing requires tunable narrow-band optical filters that are compatible with single mode fibers. We created such a filter using a disc shaped WGM resonator fabricated from a commercially available $LiNbO_3$ wafer. A Z-cut disk resonator had in $d = 4.8$ mm diameter and 170 μm in thickness.[1] The resonator perimeter edge was polished in the toroidal shape. The quality factor of the resonator modes was $Q \simeq 5 \times 10^6$. The filter operated at the 1550 nm wavelength regime and had -12 dB fiber-to-fiber insertion loss. The filter can be electro-optically tuned at 10 GHz with approximately 40 MHz/V tuning rate. To demonstrate the filter performance, we have configured it as a photonic microwave filter for transmission of a video signal at a microwave band.[2] Such a photonic architecture allows for a construction of a uniform technological platform for RF through millimeter-wave systems, that would require different sets of bulky and expensive hardware if implemented directly at RF frequencies.

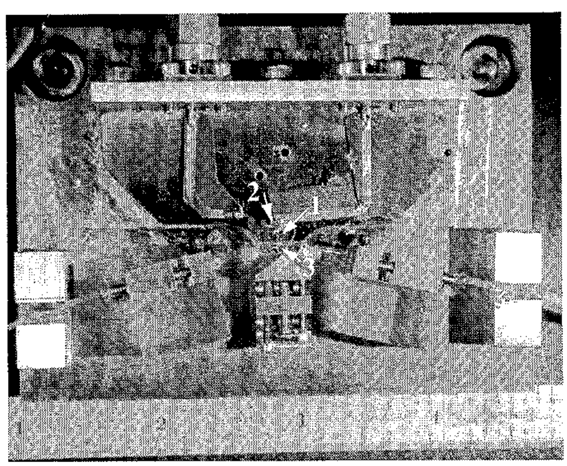

Figure 1. Fully integrated electro-optical modulator based on a whispering gallery mode cavity. The numbers stand for: (1) – the WGM cavity, (2) – the microstrip microwave resonator, and (3) – the coupling prism

We have implemented an electro-optic modulator based on WGM $LiNbO_3$ disc resonator. We observe an efficient modulation of light with coherent microwave pumping at 9 GHz with applied microwave power of about 10 mW.[1] The modulator has a fiber-to-fiber insertion loss of 5.5 dB. Its optical quality factor Q depends on a chosen mode and varies from 5×10^6 to 9×10^6. The quality factor of the microwave resonator is approximately

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equal to $Q_M \simeq 70$. Used as a receiver, the modulator allows us to detect nanoWatt microwave radiation.[3] The modulator (see in Fig. 1) is fully integrated with input optics and a build in copper platform. To our knowledge, this is the first example of integration of a high-Q crystal WGM cavity into a photonic device. The performance of the EOM remains stable during weeks of operation, and the quality factors of WGMs do not degrade with time. In principle, the size of the platform may be significantly reduced.

We have performed preliminary experimental studies of an OEO based on the high-Q WGM electro-optic modulator. The scheme of the OEO is shown in Fig. 2. At the present stage the OEO is not optimized. Light is sent directly to the photodiode after the modulator. Because the modulation is primarily of the phase type, conversion of the modulated light into microwaves is inefficient. It is worth noting here that for phase modulation and critical coupling the demodulated microwave power is absent. To make our system oscillate either a microwave amplifier must be included in the OEO loop or the optical pump power should be increased.

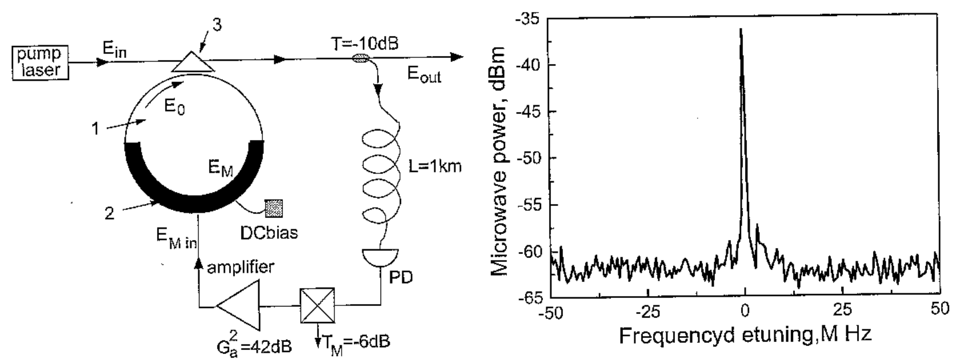

Figure 2. Scheme of WGM OEO and spectrum of the microwave signal generated in the OEO. The numbers in the picture correspond to the numbers in Fig. 1

To estimate the efficiency of the modulator for application in the OEO we measured the dependence of the demodulated signal from the photodetector as a function of power of the microwave signal ($E_{M_{in}}$ in Fig. 2) sent into the modulator. Because of the small power of the pump laser radiation (2.5 mW) and nearly complete phase modulation of light, the difference between the input and output microwave power is more that 35 dB. We obtained self sustained oscillation in the system with 42 dB microwave amplification. The length of the optical delay line is $L = 1$ km. We used a -10 dB optical splitter and a -6 dB microwave splitter to monitor the properties of the generated microwave power, and the modulated light. The spectrum of the generated microwave signal is shown in Fig. 2. The width of the microwave signal is determined primarily by the pump laser noise. The minimum measured width was approximately 100 kHz. The scheme should be optimized to reduce the width and the oscillation threshold.

In conclusion, we have studied properties of photonic devices based on whispering gallery mode $LiNbO_3$ resonators. Those devices may operate in different dynamical ranges and may produce and/or control microwave signals at frequencies up to 100 GHz. The reported work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA and with National Research Council support.

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